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Fractal-Based Planning of Urban Water Distribution System in China

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Abstract

In the research, fractal theory was adopted in water supply network. K-means algorithm was adopted to make the nodes multistage cluster zoning, and prioritize nodes was determined according to the actual situation of each zone level division. In each zone, prim algorithm completed each sub-region of water supply pipe network based on the use of fractal growth of self-organization. The established water supply network could be operated and managed according to the form of partition. The fractal self-growth model was applied to the water distribution system planning of one north city in China, the results clearly show the economic effectiveness.

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Keywords: Water supply network; district planning; k-means algorithm; level analysis; fractal theory; prim algorithm.

1. Introduction

As the growth of water distribution system in China, the topology of water supply network is becoming more complex, and it increases the operational difficulty. Nowadays, the water supply network of some cities in China has been partitioned, but it is difficult to partition the water supply network which has been build-up. Fractal theory can be applied to plan the water supply networks taking simultaneously into account the partitioning management [1-3].

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2. Water demand point level research of planning area

In China, the water demand points distribute intensively in city and they mainly include demand in households. The urban water supply network is looped while it is branched in suburb. The network develops according to its pattern, and it fits the application of fractal theory. This paper makes use of fractal growth of self-organization model to solve the contradiction of planning and partitioning. The premise is to confirm the position, elevation, flow and property of water demand point, and then it analyses the water demand point level.

2.1. Clustering analysis of water demand point

Clustering analysis is the task of grouping a set of objects in such a way that objects in the same group are more similar to each other than those in other groups. Main methods of clustering analysis include classification method, hierarchical method, density-based method, gridding-based method and model-based method.

It is adopted here the K-means algorithm to cluster the water demand point in planning area. The step of K-means algorithm are ordered as follows:

- Water consumption and water leakage are zero mean value random variables;
- Selects k point as initial centers of k group randomly;
- Calculate Euclidean the distance between the other points to the k initial centers on the basis of position, and then classify the objects according to the minimum distance;
- After all the water demand point have been distributed, calculate the position of centers again;
- If the position is changed, repeat step 2, otherwise, turn to step 5;
- Output result.

The flow of K-means algorithm is as Fig. 1.

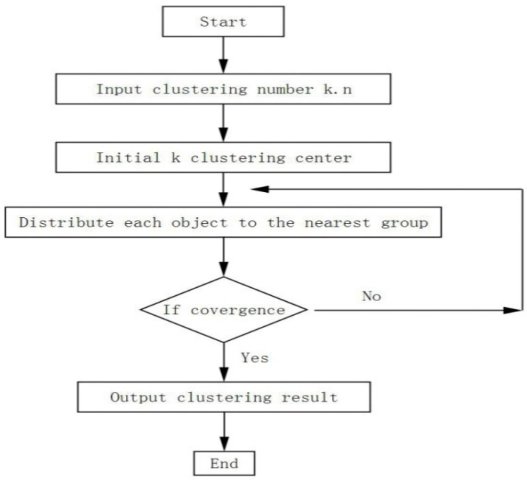

Fig.1 water demand node clustering flow

2.2. Water demand points analytical hierarchy

Some water demand points are more significant in the water supply network, such as the water demand point for hospitals and important industrial enterprises. The importance degree of demand in households is low. If urban water distribution system breaks down, the water demand points which are more important has priority to be supplied. So it has to analyze water demand point hierarchy after clustering analysis. Analytical hierarchy process is described in the following sections.

2.2.1. Establish hierarchical structure model

There are two hierarchies in the structure model, namely Goal hierarchy and Criteria hierarchy. The element in Criteria is dominated by the factor in Goal. The hierarchical structure model is as Fig. 2.

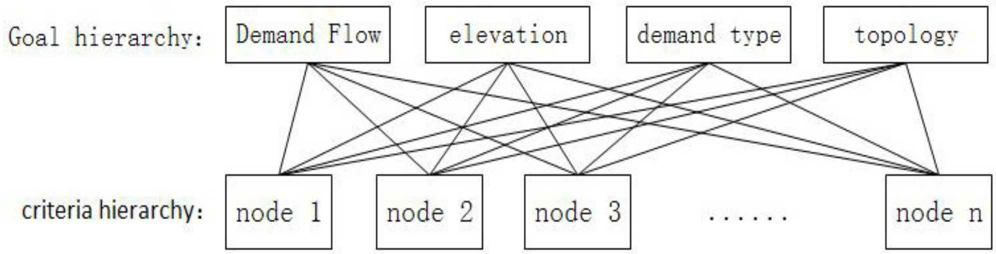

Fig.2. The analytical hierarchy process model of choosing the most important node

2.2.2. Construct judgment matrix

After hierarchical structure model has been established, it has to justify the degree of importance between two points. The element in judgment matrix A is chosen according to Table 1.

Table 1. The subscript degrees of judgment matrix

Scale	meaning
1	Element *i* and *j* is the same important
3	Element *i* is a little more important than element *j*
5	Element *i* is more important than element *j*
7	Element *i* is much more important than element *j*
9	Element *i* is far more important than element *j*
2 4 6 8	Intermediate value of the judgement above
reciprocal ($1/a_{ij}$)	The result which element *j* compare to element *i*

The form of judgment matrix A is:

$$A = \begin{pmatrix} a_{11} & \cdots & a_{1n} \\ \vdots & \ddots & \vdots \\ a_{n1} & \cdots & a_{nn} \end{pmatrix}$$

2.2.3. Calculate eigenvector of matrix A

Normalize each column of matrix A:

$$\overline{a}_{ij} = \frac{a_{ij}}{\sum_{i=1}^{n} a_{ij}} \quad i = 1,2,\cdots,n \; ; \; j = 1,2,\cdots,n \tag{1}$$

Sum each row of normalized matrix:

$$\overline{a}_i = \sum_{i=1}^{n} a_{ij} \quad i = 1,2,\cdots,n \tag{2}$$

Normalize the vector form (2) to get eigenvector:

$$W_i = \frac{\overline{a}_i}{\sum_{i=1}^{n} \overline{a}_i} \quad i = 1,2,\cdots,n \tag{3}$$

2.2.4. Sort hierarchy

Judge the importance degree of each factor of criteria hierarchy according to actual urban planning and establish judgment matrix B; B is 4×4. Calculate the eigenvector of B, $W_B = (b_1, b_2, b_3, b_4)^T$.

It establish judgment matrix A_1, A_2, A_3, A_4 which corresponds to flow, elevation, topology and user type of water demand point. A_1, A_2, A_3, A_4 are matrixes of $n \times n$, and n is the number of water demand point in some zone. The value of element in judgment matrix A_1, A_2, A_3, A_4 is according to these principle: the water demand points whose flow is larger are more important; the water demand points whose elevation is higher are more important; the water demand points which are distributed in hospital or industry zone are more important; the water demand points which are near source of water are more important. Eigenvectors of matrixes A_1, A_2, A_3, A_4 are $W_m=(a_1^m, a_2^m, a_3^m, a_4^m)^T$, m=1,2,3,4. It calculate S_j of each point in some zone, $S_j = \Sigma^4_{m=1}\ a_j^m\ b_m,\ j=1,2,\ldots,n$. The most important point in some zone is the point whose S_j is the largest.

It applies analytical hierarchy process to confirm the importance of each water demand point. Fractal growth of self-organization model starts from the prioritized point of the zone, and grow to lower-level prioritized point. It ensures the security of water supply and develops efficiency of water supply.

3. Study on fractal growth of self-organization model

3.1. Establishment of fractal growth of self-organization model

Water supply pipes are generally paved along the road, and it cannot be applied through beneath of buildings. It is a very important limit.

Each water supply network zone is a dissipative structure. There are competitions and cooperation which the formation of pipe is based on among water demand points. Then the growth of network has been transformed to the formation of the pipes. The entire water supply network has been established until all the water point demand has been met [4-6].

The connection probability between two points is defined by flow intensity $1/W_{ij}$, which show water demand intensity between two points. It will be possible to establish a pipe between two points if the value of $1/W_{ij}$ is larger. The numerical relationship is like formula (4).

$$\frac{1}{W_{ij}} = \frac{Q_i \cdot Q_j}{L_{ij}^2} \tag{4}$$

In the formula:
W_{ij} : weight between point i and point j, h^2/m^4;
Q_i, Q_j : the demand flow of point i and j, m^3/h;
L_{ij} : the distance of point i and j, m.

The flow intensity can be applied to confirm the layout of network and the importance of pipe. In fractal growth of self-organization model, it only calculate the flow intensity between two points which can be connected by roads, and the complexity of computing can be reduced.

3.2. Solution of fractal growth of self-organization model

Fractal growth of self-organization model has been established after the information of demand flow, point position and flow intensity has been gathered. Prim algorithm has been applied to solve this model. It defines V as a set of all the water demand point in some zone. In prim algorithm, the set V is a universal set. Set V has been divided into two subset T and T', T is the set which contains the points belonging to the present water network topology, and T' is complementary set of T. There is $V = T \cup T'$.

The calculation process of prim algorithm in each zone is as follows:

- Select the most prioritized demand point u_0 into set T, and then choose the edge (u_0, v_0) which has minimum weight and is connecting to u_0. The other point of (u_0, v_0) is point v_0. Add point v_0 into set T;
- Then select one demand point u from T, and select one demand point v from T'. There are minimum weight edge (u_0, v_0) (u, v) between point u and v. Add point v into set T. Repeat steps above until all the points are added into set T.

In practice, there are thousands of points in planning area, so the achievement of prim algorithm needs computer programming.

4. Case study and conclusion

4.1. Case study

Fractal theory is applied into one north city water distribution system planning. The distribution of water demand points are shown in Fig. 3. The partition of the points by K-means algorithm are shown in Fig. 4. It combined urban road planning with fractal growth model to get ultimate topology of the network. It is shown in Fig. 5.

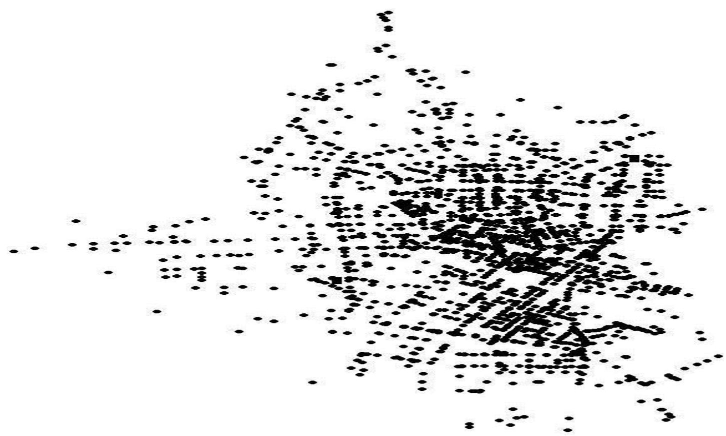

Fig.3. The node distribution

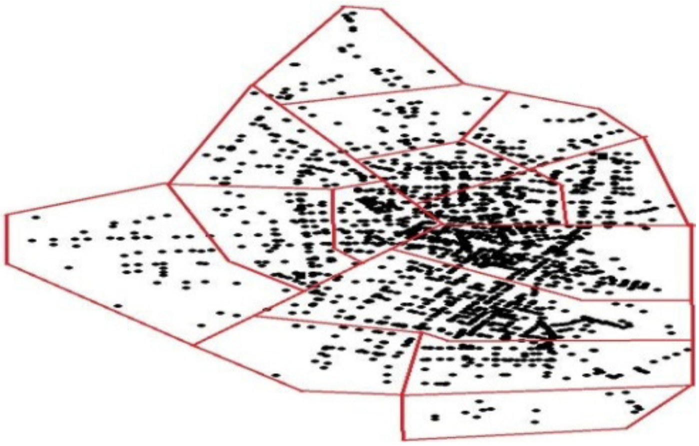

Fig.4. Schematic diagram of nodes zoning

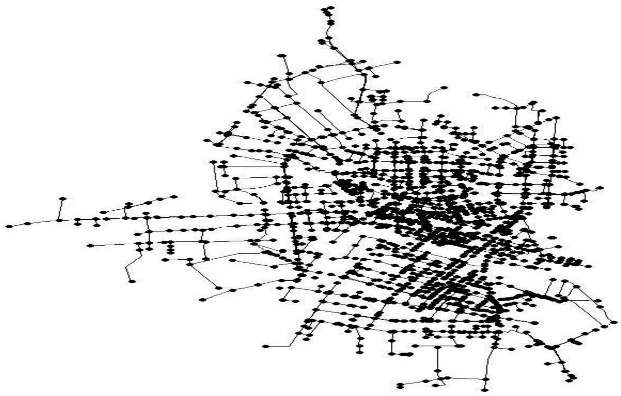

Fig.5. The network of water distribution system

4.2. Conclusion

In order to overcome the disconnection of water network planning and partition, the paper applies fractal theory to guide the planning of urban water distribution system. Firstly, the information is gathered to ensure the position and flow of water demand position, then according to the property of demand flow and elevation, these point are partitioned. In each zone, analytical hierarchy process has been applied to confirm the importance of each point. The water supply network fits to fractal growth of self-organization, so fractal theory can be applied to establish the topology of the network. Finally, combined with information of water sources, entire water distribution system planning scheme can be established. It is applied in practical planning and it has significant effect.

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